USES OF SUPPORT MATERIAL IN SOLID FREEFORM FABRICATION SYSTEMS

FIELD OF THE INVENTION

The present invention is generally related to solid freeform fabrication systems. More particularly, the present invention relates to systems for forming three-dimensional objects using ink-jet technology.

BACKGROUND OF THE INVENTION

Solid freeform fabrication (or layer manufacturing) can be defined generally as an additive fabrication technology used to build a three-dimensional object using layer by layer or point by point fabrication. With this fabrication process, complex shapes can be formed without the use of a pre-shaped die or mold.

Essentially, with such a system, an object can be designed using a computer program, such as a Computer Aided Design (CAD) application. Once the object has been designed three-dimensionally, solid freeform fabrication technology enables the translation of the computer generated model into a three-dimensional object. This technology is useful in areas such as verifying a CAD model, evaluating design feasibility, testing part functionality, assessing aesthetics, checking ergonomics of design, aiding in tool and fixture design, creating conceptual models and sales/marketing tools, generating patterns for investment casting, reducing or eliminating engineering changes in production, prototyping, and providing production runs, to name a few.

Selective deposition techniques generally include the dispensing of a binder material into a powder or slurry build material to form the object, or alternatively, bulk-jetting build material itself to form the object. Bulk-jetting systems can have

optional curing and/or milling systems, which can be used to harden the build material and/or level the build material, respectively. With bulk-jetting systems, removable support material is typically deposited during the formation of the object to support overhangs of build material as the build material hardens.

SUMMARY OF THE INVENTION

It has been recognized that as support material is already being used for in solid freeform fabrication systems, it would be desirable to provide alternative uses of this material to broaden its scope of use. As such, a solid freeform fabrication system for producing a three-dimensional object can comprise build material configured to be deposited in layers to form a three-dimensional object; and support material configured to be deposited adjacent to the build material for supporting the build material during formation of the three-dimensional object. The support material can also be used to form a feature that imparts a predetermined property within the three-dimensional object.

In an alternative embodiment, a method for solid freeform fabrication of three-dimensional objects can comprise multiple steps. One step can include layering build material to form a three-dimensional object, wherein the three-dimensional object includes a cavity therein that is at least in part defined by the build material. Additional steps can include supporting overhangs formed during the layering process with a first portion of support material, and depositing a second portion of the support material in the cavity, wherein at least the second portion of the support material is configured to form a feature that imparts a predetermined property within the three-dimensional object. To liberate the formed three-dimensional object, a step of removing the first portion of the support material from the three-dimensional object can be carried out.

Additional features and advantages of the invention will be apparent from the detailed description and figures that follows, which illustrates, by way of example, features of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

Aspects of the invention can be better understood with reference to the following drawings. The components in the drawings are not necessarily to scale, emphasis instead being placed upon clearly illustrating the principles of the present invention.

FIGS. 1a to 1h depict a solid freeform fabrication system in accordance with embodiments of the present invention;

FIG. 2 depicts the solid freeform fabrication of a golf tee in accordance with embodiments of the invention, exemplifying the use of the support material to support overhangs of build material, as well as provide a permanent predetermined property within a cavity of the three dimensional object;

FIG. 3 depicts an alternative embodiment wherein support material and build material is deposited within a build material-formed cavity of a three-dimensional object; and

FIG. 4 depicts an alternative embodiment wherein a conductive support material is formed within a cavity of a three-dimensional object.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT(S)

Before the present invention is disclosed and described, it is to be understood that this invention is not limited to the particular process steps and materials disclosed herein because such process steps and materials may vary somewhat. It is also to be understood that the terminology used herein is used for the purpose of describing particular embodiments only. The terms are not intended to be limiting because the scope of the present invention is intended to be limited only by the appended claims and equivalents thereof.

It must be noted that, as used in this specification and the appended claims, the singular forms "a," "an," and "the" include plural referents unless the context clearly dictates otherwise.

The term "solid three-dimensional object" or "three-dimensional object" refers to objects that are formed by one of the printing methods of the present invention. Solid three-dimensional objects can be sufficiently firm so as to maintain a fixed volume and shape to an extent which is appropriate for use in solid freeform fabrication. In some embodiments, such three-dimensional objects need not be strictly rigid, such as in cases where the object formed is self supporting at minimum, or alternatively, flexible.

"Hardening," "curing," "solidifying," or the like, refers to a change that occurs when the build material and/or the support material are chemically or physically modified from a more liquid state to a more solid state. The process of hardening, curing, or solidifying can occur as a result of electromagnetically irradiating liquid build material to cause curing, e.g., UV curing, by overprinting or underprinting a reactive chemical with a liquid build material, e.g., epoxy build material jetted with an amine, or by cooling or freezing the liquid material after jetting, for example.

"Build material" includes substances that can be used to form the bulk of the solid three-dimensional object. These build materials typically include groups that can be cured or hardened as a result of exposure to electromagnetic irradiation, such as UV radiation, or as a result of a chemical reaction with a curing agent. Build materials can include a liquid modifier(s) admixed therewith when it is desired to alter color and/or jettability properties, such as with respect to viscosity, surface tension, and the like. Temperature adjustment can also be used to alter the jettability properties as well.

"Support material" includes substances that are deposited, such as by ink-jet architecture, for the purpose of supporting overhangs of a solid three-dimensional object during the build process. This material is typically configured such that it can be relatively easily removed after the build process is complete. Materials that can be used include the use of wax, patterned hardening

composition, water swellable gel, readily meltable material, readily soluble material, or another material that can carry the solid three-dimensional object being built, as well as be configured to be readily removed. Removal can be by heating, chemical reaction, power washing, dissolution, or other similar methods. However, in accordance with embodiments of the present invention, depending on the location of support material deposition, the build material can be deposited in a position such that the support material will remain with the three-dimensional object as a more permanent feature.

A "build platform" is typically the rigid substrate that is used to support the solid three-dimensional object being formed (including build material and support material).

The term "substrate" can include the build platform, previously deposited support material, and/or previously deposited build material, depending on the context. For example, in one embodiment, support material can be applied to a build platform to enable easy removal of the solid three-dimensional object from the build platform. In this case, the build platform is the substrate for the support material. Alternatively, previously deposited build material and/or support material can be a substrate for subsequently applied build material and/or support material. To illustrate, when laying down an initial layer of a build material and/or support material, the initial layer will typically be carried by a build platform or a removable material on the build platform. However, subsequent layers of build material and/or support material can be deposited onto the previously deposited layer substrate.

The term "at least partially transparent" refers to materials that can be viewed into and/or viewed through. For example, materials that are from completely transparent to translucent to nearly opaque would be considered at least partially transparent. At least partially transparent build material can be used in any embodiment of the present invention, but is particularly useful in embodiments wherein a colored support material is present within a cavity of the build material, and thus, can be viewed through a wall formed by the build material.

The terms "jetting," "ink-jetting," "bulk-jetting," or the like, refer to a process of jetting liquid build material or support material from jetting architecture, such as an ink-jetting architecture. After jetting, the jetted material can be hardened or solidified to become part of a three-dimensional object formed by solid freeform fabrication in accordance with embodiments of the present invention.

The term "cavity" refers to an opening defined by build material. The cavity can be completely defined by build material, e.g., a closed cavity, or partially defined by build material, e.g., an open cavity.

As used herein, "liquid modifier" refers to any composition that can be prepared for jetting with a build material or a support material, and which, in combination, can be jetted from a dispensing architecture, such as an ink-jet architecture. Optionally, the liquid modifier can be a colorant to be jetted with the build or support material. A wide variety of other liquid modifiers can be used with the systems and methods of the present invention. For example, such liquid modifiers that can be used include water, surfactants, organic solvents and co-solvents, buffers, biocides, sequestering agents, viscosity modifiers, as well as soluble low molecular weight monomers, oligomers, and polymers, etc.

Though liquid modifiers are described herein in some detail, it is not always required that a liquid modifier be used. In some embodiments, the build material or the support material can be configured to be jetted from an ink-jet architecture without the use of a liquid modifier. For example, a wax can be heated to a jettable temperature and cooled upon application to form a solidified build material object or support material. However, if such liquid modifiers are used, they are typically present in small amounts. An example where a liquid modifier can be added is with respect to embodiments wherein it is desired to alter the viscosity, surface tension, or the like, of the build material and/or the support material. This being stated, modification of jettable compositions with a liquid modifier is not required, and in some cases, can be undesirable.

With these definitions in mind, a solid freeform fabrication system for producing a three-dimensional object is provided. The system can comprise build

material configured to be deposited in layers to form a three-dimensional object; and support material configured to be deposited adjacent to the build material for supporting the build material during formation of the three-dimensional object. The support material can also be configured to form a feature that imparts a predetermined property within the three-dimensional object, such as a color or conductivity, for example.

Alternatively, a method for solid freeform fabrication of three-dimensional objects can comprise various steps, including layering build material to form a three-dimensional object, wherein the three-dimensional object includes a cavity therein that is at least in part defined by the build material. Method steps can also include supporting overhangs formed during the layering process with a first portion of support material, and depositing a second portion of the support material in the cavity, wherein at least the second portion of the support material is configured to form a feature that imparts a predetermined property within the three-dimensional object. Additionally, a step of removing the first portion of the support material from the three-dimensional object can be carried out. In one embodiment, the first portion and second portion of the support material are of the same composition.

Reference will now be made to the exemplary embodiments illustrated in the drawings, and specific language will be used herein to describe the same. It will nevertheless be understood that no limitation of the scope of the invention is thereby intended. Alterations and further modifications of the inventive features illustrated herein, and additional applications of the principles of the invention as illustrated herein, which would occur to one skilled in the relevant art and having possession of this disclosure, are to be considered within the scope of the invention.

Referring now to FIGS. 1a to 1h, a system in accordance with an embodiment of the present invention is shown, wherein sequential application of build material, indicated generally at 14a to 14g, and support material, indicated generally at 16a to 16e, are applied to a build platform 12. In a typical

embodiment, a layer of build material and/or support material is applied, and the build platform is lowered (or the printing architecture is raised) in preparation for applying a subsequent layer. Specifically, FIG. 1a exemplifies a build platform which provides a substrate for application of support material 16a. FIG. 1b depicts the same build platform at a later point in time, wherein build material 14a has been applied to support material 16a. FIG. 1c depicts the build platform at a later point in time, wherein additional build material 14b and additional support material 16b has been applied. FIG. 1d and 1e illustrates the fabrication at respective later points in time, wherein additional build material 14c, 14d, and additional support material 16c, 16d are applied. FIG. 1f depicts an additional build material layer 14e after application, which acts to enclose a support material mass or feature 16e within a cavity 20. If the build material is at least partially transparent, then the build material will be viewable through three-dimensional object walls formed by the collective layers of build material. FIG. 1g depicts the application of more build material 14f and more support material 16e. Support material 16e is used to support an overhang 22 of build material 14g, as shown in FIG. 1h.

The application of the layers shown in FIGS. 1a to 1h can be by known methods, such as by jetting build material and support material from ink-jet architecture. These selective liquid-ejection systems can have a planing and/or milling process between the applications of each layer, which can be implemented to compensate for variations in drop volume or directionality that can subsequently result in variations in layer thickness. For example, to compensate, layers can be intentionally printed overly thick and then planed down to a known controlled height using a planing or milling process, e.g., using a heated roller. Additionally, upon application of each layer, a curing process can be used, such as a UV curing process (using a UV lamp) or chemical curing process (using a separately jetted curing agent). In either embodiment, the support material can be applied within cavities to form features within the build material, in accordance with embodiments of the present invention.

The following examples depict a few three-dimensional printing models that can be used in accordance with embodiments of the present invention. It should be noted that this list of embodiments is not considered to be exhaustive, but rather exemplary. While all of the examples describe the dispensing and layering of build material and support material together at the first layer, this is not required. For example, it may be desirable to dispense support material along the entire first layer in order to provide a layer that can be easily removed to separate the build material from the build platform.

Referring specifically to FIG. 2, a side cross-sectional view of a system in accordance with embodiments of the present invention is exemplified. A blow up of a section of the cross-sectional view is also provided to depict the layering system more fully. This depiction is not necessarily to scale, but is shown primarily for exemplary purposes. In this embodiment, a build platform 12 is shown for supporting the solid three-dimensional object being formed, which in this case, can be a monogrammed or personalized golf tee. The object is formed by applying layers of both build material 14 and support material 16a, 16b. A first portion of the support material 16a can be used to support overhangs of the build material used to form the three-dimensional object. A second portion of the support material 16b can be formed within a cavity 20 within the build material to form a feature 18 that imparts a property, such as a symbol having a certain color or colors. In this embodiment, the support material 16b can be formed in the shape of a personalized monogram, trademark, slogan, symbol, or the like. The only limitation as to what can be present is related to the boundaries of the build material, and the thickness of the individual layers 24 of material. For example, a line cannot be thinner than that which is capable of being printed by the ink-jet printing system used to lay down the individual layers. In this embodiment, the build material can be of an at least partially transparent material, which can range in opacity from transparent to translucent to nearly opaque. Colored or other see through materials can also be used. In other words, as long as the colored symbol

(which in this case is a diamond) can be seen through the build material, it is within the scope of the present embodiment.

In one embodiment, colored parts and/or regions can be created by intentionally embedding colored support material in enclosed internal cavities. Based on the ratio of build to support material within the build material, and the depth of this internal cavity below the surface, a desired degree of color can be generated. Such a system and method can enable a cheap multi-color solution to existing single color deposition methods.

In an alternative embodiment, the colored support material can be formed to be exposed at a surface of the three-dimensional object so that it can be seen having a predetermined shape at the surface. In such an embodiment, when removing the supporting support material from the build material, care should be taken to not remove the support material that is configured to remain to provide a decorative or other permanent feature. When the feature formed by the support material is on the surface, the build material can be at least partially transparent as describe previously, or can be opaque. If the build material is opaque, the support material-formed feature will not be visible through the build material, but will be visible from the surface of the three-dimensional object. In this embodiment, the support material itself can be either opaque, or at least partially transparent.

With respect to embodiments where the support material is exposed to a surface of the three-dimensional object, a section facing a top horizontal plane of the three-dimensional object will not actually be used to support build material *per se*, as no build material will be applied atop the support material. However, support material could still be included at such a surface to provide the function of imparting an alternative property to the three-dimensional object, such as color or conductivity, etc. In these embodiments, it may be desirable to modify software used to designate the placement of the support material such that in locations where the support material does not actually support build material, it can still be so placed. If, on the other hand, a section of the cavity that is open on a surface is still used to support build material, e.g., vertical surface, angled surface, or bottom

surface, then the open section can be filled with support material for its supporting function, as well as its alternative property imparting function.

In another embodiment, voids or cavities can be formed within a three-dimensional object using software. In this sense, objects can be formed using but one build material, and variations in the appearance of the build material can be provided by placement of support material in strategic locations within the object. This can be planned using computer modeling. For example, a single material (the build material) that can be made to have the appearance or the function of having multiple materials by creating voids within the three-dimensional object that are automatically filled with support material. In this embodiment, voids can be formed in a CAD model prior to printing.

In another alternative embodiment, a cavity formed by the build material can be filled with a network of both support material and build material, as exemplified in FIG. 3. Specifically, FIG. 3 depicts an embodiment wherein both support material 16b and build material 14b are both within a common cavity 20. In this embodiment, collectively, the build material 14b and support material 16b form the feature 18. Again, a build platform 12 is used to support the object as it is being fabricated, and support material 16a and build material 14a are used as previously described, and as is known in the art. In such an embodiment, both support material 16b and build material 14b can be dispensed in a half-tone density, ranging from 1:99 to 99:1 of build material to support material by volume. To illustrate, in one embodiment, 5% by volume for 20 layers of support material can be dispensed with 95% by volume of build material to form a half-tone density of 95%. As long as the half-tone patterns are appropriately shifted from layer to layer, the overall result can be designed to be relatively strong and uniformly colored region. Alternatively, by changing the ratio of support material 16b to build material 14b within the cavity (as shown in FIG. 3), the saturation of the colored portion of the part could be modified and variable, with the limitation of color and saturation being dependent on the base color of the build and support material selected for use. In still another embodiment, by changing the depth of the cavity

below the surface of the object, the hue of the part could be modified and variable. For example, in the case of a yellow-translucent build material and a cyan support material, the apparent hue of the support material of the feature inside the part could range from near cyan (at points of the cavity nearer the surface) to near green (at points of the cavity embedded under more and more yellow build material).

There are several advantages that can be realized by the system and method exemplified in FIGS. 2 and 3. For example, such a system and method allows for the adding of alternative material properties to bulk-jetting solid freeform fabrication systems without any machine cost penalty or any fabrication time penalty. More specifically, such a system and method allows for adding color to bulk-jetting solid freeform fabrication techniques without any machine cost penalty, without any fabrication time penalty, and without affecting the surface finish or dimensional accuracy of the final part (unless used in an embodiment where surface support material is included to provide a surface detail). Additionally, these systems and methods allows for using spot colors within an object for feature differentiation, labeling, revision control, and the like, without any machine cost penalty and without any fabrication time penalty.

Referring now to FIG. 4, an alternative property (other than color) can be imparted by support material in a solid freeform fabrication-produced object. Specifically, FIG. 4 exemplifies an embodiment that uses support material to form a conductive feature that passes through the three-dimensional object. More specifically, a build platform 12, support material 16a and build material 14 are used as previously described, and as known generally in the art. However, if the support material is conductive, then channels of support material 16b that pass through the build material can be used to provide conductive paths within or through the three-dimensional object. More specifically, in this example, enclosed internal channels or cavities 20 can be prepared using a computer model of the object, and the object can be formed such that these channels would be filled with the conductive support material during the fabrication process. In one

embodiment, these channels can be patterned to form functional features 18, such as RF antennas or circuits to route electrical signals through or inside of the three dimensional object. This type of function is does not require that the build material be transparent or at least partially transparent, and additionally, such a system and method allows for adding conductive material to bulk-jetting solid three-dimensional objects without any machine cost penalty and without any fabrication time penalty.

In each of the embodiments described above, the support material that is used to form a feature, such as a conductive and/or color feature, will remain as part of the three-dimensional object. However, the support material that is used to merely support the build material during fabrication will typically be removed by one of a number of known processes, including power washing, melting, chemical removal, dissolution, and the like.

With respect to embodiments wherein the dispensing system is an ink-jet or bulk-jetting printing system, various techniques can be used to modify the viscosity or other jetting properties of the build material and/or support material. For example, heat can be used to liquefy material such that it becomes ink-jettable. The selection of an appropriate heat range is generally composition specific, but can range from 25°C to 170°C. In one embodiment, if the build material is stearyl acrylate, and no liquid modifier is added, then a temperature range that can be used is from 50°C to 170°C.

Alternatively, liquid modifier components can be added to liquid build material and/or support material to modify properties, or colorant can be added to impart color to the finished three-dimensional object. Exemplary colorants that can be used include dyes and/or pigments. Examples of liquid modifier components that can be used, in small amounts if at all, include water, surfactants, organic solvents and co-solvents, buffers, biocides, sequestering agents, viscosity modifiers, as well as soluble low molecular weight monomers, oligomers, and polymers, etc. As mentioned, liquid modifiers are typically not added to carry the build material and/or the support material, but can optionally be added to modify

jetting characteristics, such as color viscosity, surface tension, or other properties.

It is to be understood that the above-referenced arrangements are illustrative of the application for the principles of the present invention. Numerous modifications and alternative arrangements can be devised without departing from the spirit and scope of the present invention while the present invention has been shown in the drawings and described above in connection with the exemplary embodiments(s) of the invention. It will be apparent to those of ordinary skill in the art that numerous modifications can be made without departing from the principles and concepts of the invention as set forth in the claims.

What Is Claimed Is: